

The Phoenix survey: the pairing fraction of faint radio sources

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ABSTRACT

The significance of tidal interactions in the evolution of the faint radio population (sub-mJy) is studied using a deep and homogeneous radio survey (1.4 GHz), covering an area of 3.14 deg^2 and complete to a flux density of 0.4 mJy. Optical photometric and spectroscopic data are also available for this sample. A statistical approach is employed to identify candidate physical associations between radio sources and optically selected ‘field’ galaxies. We find an excess of close pairs around optically identified faint radio sources, albeit at a low significance level, implying that the pairing fraction of the sub-mJy radio sources is similar to that of ‘field’ galaxies (at the same magnitude limit) but higher than that of local galaxies.

Key words: Galaxies: active – galaxies: starburst – Cosmology: observations – radio continuum: galaxies

1 INTRODUCTION

Visual inspection of faint radio sources shows that many have optical counterparts which are preferentially located in pairs or small groups exhibiting disturbed optical morphologies, suggestive of interactions or mergers (Kron et al. 1985; Gruppioni et al. 1999). Although this is not an ideal method for identifying physically associated groups, the frequency of cases suggests that such phenomena are at least partially responsible for the enhanced star formation rate seen in these objects (Kron et al. 1985; Windhorst et al. 1995). There is also independent evidence that tidal interactions affect both the nuclear galaxy activity and the disk star-formation rate. For example spectroscopic studies of interacting systems show significant excess of nuclear optical-line emission (e.g. $H\alpha$) compared to ‘field’ galaxies (Keel et al. 1985), due to either nuclear star-formation or a non-thermal central source. A systematic enhancement is also seen in the disk $H\alpha$ and far-infrared emission (e.g. Kennicutt et al. 1987; Bushouse et al. 1988), attributed to increased star-formation in the galactic disk. Similarly, galaxy interactions are shown to enhance the radio emission from the nucleus of galaxies, which is mainly caused by star formation activity within the nuclear region (e.g. Hummel et al. 1990). Recently, Gallimore & Keel (1993) demonstrated that about 30% of infrared ($60 \mu\text{m}$) selected galaxies are found in pairs showing an increase in their pairing fraction with in-

creasing $60 \mu\text{m}$ luminosity. The pairing fraction of infrared selected galaxies is comparable to that derived for optically selected starbursts (Keel & van Soest 1992). Moreover, a similar study of a redshift-limited sample of Seyfert-type galaxies (Dahari 1984) has revealed an increased fraction of close companions ($\approx 15\%$) compared to a control sample of ‘field’ galaxies.

Galaxy interactions and mergers can be studied, in the absence of redshift information, using a statistical approach. This is to estimate the probability that galaxies, with angular separation θ , are physically associated, rather than randomly aligned on the sky plane. This technique has been applied to deep magnitude limited surveys, to study the evolution in the rate of galaxy mergers with redshift (Zepf & Koo 1989; Burkey et al. 1994; Roche et al. 1998). In this paper we employ this method to estimate the pairing fraction of the sub-mJy sources detected in a deep and homogeneous radio survey (Phoenix) with available multi-wavelength data. This technique has the advantage of being more quantitative and objective in identifying candidate interacting systems, compared to simple visual inspection. The latter method is sensitive to the depth of the survey, the wavelength of the observation and most crucially to the observer’s criteria for identifying potentially interacting galaxies.

The observations are described in section 2. The statistical method for identifying candidate interacting galax-

ies is discussed in section 3, while section 4 estimates the minimum angular separation for which close pairs can be resolved. The results are presented in section 5 and discussed in section 6. Finally, section 7 summarises our conclusions. Throughout this paper we assume a value $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$.

2 OBSERVATIONS

2.1 Radio observations

The radio observations were made at 1.4 GHz using the 6A configuration of the Australia Telescope Compact Array (ATCA). The mosaic of 30 pointing centres covers a 2° diameter area centred at $\text{RA}(2000) = 01^{\text{h}} 14^{\text{m}} 12^{\text{s}}.16$; $\text{Dec.}(2000) = -45^\circ 44' 8''.0$. The synthesised beam FWHM for each of the pointing centres is ≈ 8 arcsec.

Details of the observations, image formation, source extraction and catalogue generation are presented in Hopkins et al. (1998). A source is included in the catalogue if its peak flux density is 4σ above the local RMS noise. A total of 1079 sources with flux densities $S_{1.4} > 0.1 \text{ mJy}$ are detected. There are two kinds of incompleteness in the catalogue, as with any sample limited by peak flux density. The first is a loss of sensitivity due to the attenuation of the primary beam away from a pointing centre. This has been minimised in the Phoenix survey by the mosaicing strategy used. The second is the fact that extended objects with a total flux density above the survey limit can be missed by an algorithm which initially detects candidates based on their peak flux density. Methods of correcting these effects have been described by Hopkins et al. (1998). The radio catalogue is found to be $\approx 80\%$ complete to 0.4 mJy .

2.2 Optical Photometric Observations

The optical survey of the Phoenix field was carried out at the Anglo-Australian Telescope (AAT) in the *R*-band. Details about the observations and data reduction are presented in Georgakakis et al. (1999). The source extraction and photometry is performed using the FOCAS package (Jarvis & Tyson 1981). The star-galaxy separation is carried out to the limiting magnitude $R = 20.0 \text{ mag}$. At fainter magnitudes no attempt is made to further eliminate stars from the sample, since compact galaxies could be mistakenly removed (Georgakakis et al. 1999). The resulting galaxy catalogue, complete to $R = 22.5 \text{ mag}$, is used to optically identify the sources detected in the radio survey as described in Georgakakis et al. (1999). A total of 504 radio sources (47%) have been identified to $R=22.5 \text{ mag}$.

2.3 Optical Spectroscopic

The spectroscopic data were obtained using slit spectroscopy at the ESO 3.6 m telescope and multi-object fibre spectroscopy at the 2 degree field spectroscopic facility (2dF) at the AAT. Details about these observations are presented by Georgakakis et al. (1999). Redshifts were established for 228 out of 320 candidate optical identifications. The optical spectral features of these sources were employed to classify them as (i) absorption-line systems likely to be ellipticals;

(ii) star-forming galaxies; (iii) Seyfert 1 and 2 type galaxies; and (iv) unclassified objects. The unclassified objects displayed at least one identified emission line (allowing a redshift to be determined), but poor S/N, or a very small number of emission lines within the observable window, or the presence of instrumental features contaminating emission lines, prevented us from carrying out a reliable classification.

3 THE METHOD

To determine whether two galaxies are closely aligned on the sky by chance or are physically associated, we follow the method employed by Burkey et al. (1994). Given a random distribution of unrelated galaxies on the sky, the probability of a galaxy pair being chance projection is

$$P = \int_0^\theta 2\pi\alpha\rho \exp(-\pi\rho\alpha^2)d\alpha = 1 - \exp(-\pi\rho\theta^2), \quad (1)$$

where θ is the angular separation between the galaxies of the pair, with ρ being the surface density of galaxies brighter than m , the magnitude of the fainter of the two galaxies. The integrand is the probability of finding a galaxy in a ring of width $\delta\alpha$, assuming Poisson statistics (Scott & Tout 1989). Equation (1) has a correction that accounts for the normal galaxy clustering, as estimated by the angular correlation function at relatively large angular separations. Although this correction is not included in equation (1), as will be discussed in section 5, our analysis takes into account the clustering of optically selected galaxies. The surface density, ρ , in equation (1) is calculated by integrating the counts to the limiting magnitude of the faintest member of the pair. This is a conservative approach since the contribution of pair members projected by chance is overestimated (Burkey et al. 1994). In equation (1) we assume that the minimum angular separation, β , over which individual galaxies can successfully be resolved, is zero. However, β depends on both the atmospheric seeing conditions and the splitting efficiency of the source extraction software and is discussed in the next section. Therefore equation (1) is corrected for the resolution effect as

$$\begin{aligned} P &= \int_\beta^\theta 2\pi\alpha\rho \exp(-\pi\rho\alpha^2)d\alpha \\ &= \exp(-\pi\rho\beta^2) - \exp(-\pi\rho\theta^2). \end{aligned} \quad (2)$$

To avoid biases due to incompleteness, we consider the optically identified radio sample with $S_{1.4} \geq 0.4 \text{ mJy}$ and $17.0 \leq R \leq 21.0 \text{ mag}$, comprising a total of 206 sources. Regions contaminated by bright stars and vignetted corners are masked out. A probability cutoff $P \leq 0.05$, provides a sample of pairs that are least likely ($\leq 5\%$) to be spurious alignments. To check the sensitivity of our results to the adopted probability cutoff, we also consider the $P \leq 0.1$ case.

4 SIMULATIONS

The atmospheric seeing conditions at the time of the observation limit the minimum separation for which the indepen-

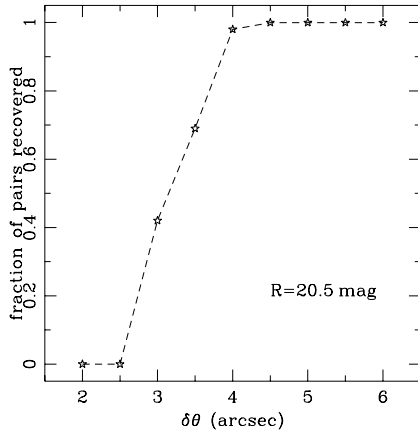


Figure 1. Percentage of successfully recovered pairs as a function of the angular separation of the components. The individual galaxies in this example have $R = 20.5$ mag.

dent components of galaxy pairs are successfully detected. For the present observations the average seeing is ≈ 1 arcsec. Although FOCAS can, in principle, split close pairs to the seeing limit, there is a trade-off between the FOCAS resolving power and the number of spurious detections due to multiple splitting of extended sources. The FOCAS splitting parameters are therefore, chosen to minimise this effect, albeit in the expense of resolving power. To quantify the FOCAS splitting efficiency we use IRAF software to construct artificial galaxy images separated by angular distances between 2–6 arcsec and magnitudes in the range $R = 17.0$ – 21.0 mag. Then, we attempt to recover the individual members of the pair using the FOCAS package as with the real data-set.

The simulated galaxies are assigned an exponential intensity profile (Freeman 1970) similar to that of spiral galaxies and absolute magnitudes in the range $M_B = -21.0$ to -19.0 mag, bracketing the characteristic luminosity ($M_B^* \approx -20.0$ mag; Metcalfe et al. 1991) of the galaxy luminosity function. The peak surface density is $\mu_{o,B} = 21.5$ mag arcsec $^{-2}$, similar to that of high surface brightness galaxies (Freeman 1970). The transformation from the B filter to the R -band is performed using the $B - R$ colour at $z = 0$ of a model spectral energy distribution corresponding to Sab/Sbc type galaxies (Pozzetti Bruzual & Zamorani 1996; Georgakakis et al. 1999).

For a given M_R , galaxy pairs are generated with each of the galaxy components having magnitudes in the range $R = 17.0$ – 21.0 mag. Poisson noise was added to the image, which is then convolved with a Gaussian filter with FWHM of 1 arcsec, simulating the effect of seeing. The simulations show a minimum resolving separation of ≈ 4 arcsec. This is demonstrated in Figure 1 where the fraction of successfully split pairs is plotted against the separation of the components. For smaller separations FOCAS is unable to split the individual galaxies, implying $\beta = 4$ arcsec in equation (2). Adopting $\beta = 1$ arcsec slightly decreases the estimated number of pairs with $\delta\theta \geq 4$ arcsec, but does not alter any of our final conclusions.

5 GALAXY PAIR COUNTING

The technique outlined in section 3 is used to calculate the number of close pairs between radio sources and ‘normal’ optically selected galaxies (radio-galaxy/‘field’-galaxy pairs). The distribution of radio-galaxy/‘field’-galaxy pairs as a function of angular separation is shown by the hatched histogram in Figure 2 for the probability cutoffs $P < 0.05$ and 0.10 respectively. However, a fraction of the identified pairs are expected to be random superpositions on the sky plane. Moreover, because of the normal clustering of galaxies, quantified by the two point correlation function, $w(\theta)$, we also expect a number of non-random galaxy pairs around optically identified radio sources. Therefore, to investigate whether the pairing fraction of optically identified sub-mJy radio sources differs from that expected for ‘normal’ optically selected galaxies on average, we need to assess the significance of these two effects. For that purpose a total of 200 mock catalogues are constructed by randomly selecting galaxies in the range $17.0 < R < 21.0$ mag from the optical galaxy catalogue. Each of the mock catalogues has the same number of objects and the same magnitude distribution as the optically identified radio sample with $S_{1.4} \geq 0.4$ mJy and $17.0 < R < 21.0$ mag. Taking the galaxies of the mock catalogue in question as centres, the number of pairs with ‘field’ galaxies is calculated, using the method outlined in section 3. The mean number of close companions and the standard deviation at each angular separation is calculated from the 200 mock catalogues. The results are shown with the continuous line in Figure 2. The dashed lines represent the 1σ deviations around the mean. To improve the statistics we consider pairs in the range 4–12 arcsec, where our estimator is more sensitive in identifying candidate interacting systems (see section 6). From the mock catalogues we count a total of 25.6 ± 5.0 pairs around ‘normal’ optically selected galaxies for angular separations $4 < \delta\theta < 12$ arcsec and for $P \leq 0.05$. This compares to 43.0 ± 6.6 (Poisson statistics) pairs around radio sources. Therefore, the number of pairs around faint radio sources above the random and $w(\theta)$ expectation is $(43.0 \pm 6.6) - (25.6 \pm 5.0) = 17.4 \pm 8.3$ (2.1σ confidence level). A similar result, with a slightly larger significance (2.3σ), is obtained for $P \leq 0.10$.

6 DISCUSSION

The environment of faint radio sources has been explored in previous studies using visual inspection. Kron et al. (1985) considered a radio selected sample with $S_{1.4} > 0.6$ mJy and available four-band photometry (U , J , F , N -bands). For the sub-sample with $17.0 < R < 21.0$ mag (here we assume the transformation $R = F - 0.14$ between F and R -band magnitudes; Metcalfe et al. 1991) they found that about 19% of the sources (18 out of 95) lie in pairs or groups. More recently, Gruppioni et al. (1999) studied a radio sample with $S_{1.4} > 0.2$ mJy and multi-wavelength photometric data. They conclude that about 27% of the sources with $S_{1.4} > 0.4$ mJy and $17.0 < R < 21.0$ mag (6 out of 22 galaxies in that study) are found in pairs or small groups. The analysis described in the previous section identified 43 candidate interacting pairs out of a total of 206 sources, corresponding to a pairing fraction of 21%, in reasonable agreement with the results from the above mentioned studies.

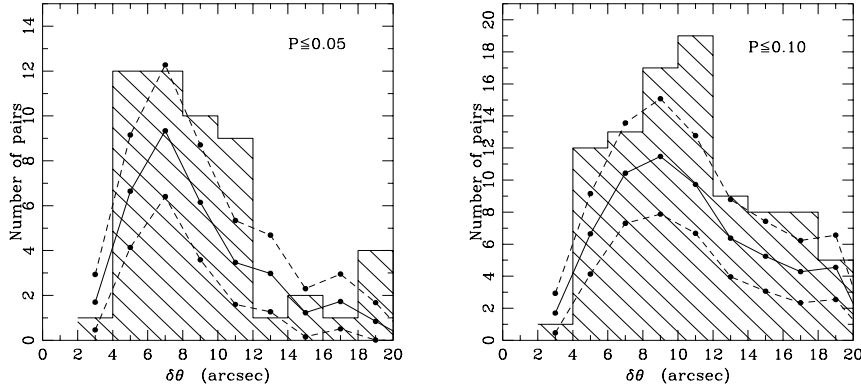


Figure 2. Number of radio-galaxy/'field'-galaxy pairs with probabilities $P \leq 0.05$ (left panel) and $P \leq 0.10$ (right panel) of being spurious alignments. The continuous line is the mean pair count derived for 'field' galaxies. The dashed lines are the 1σ envelope lines around the mean.

We also find that although the pairing fraction of the sub-mJy sources in the present sample ($S_{1.4} \geq 0.4$ mJy; $17.0 \leq R \leq 21.0$ mag; $\delta\theta \geq 4$ arcsec) is higher than that of optically selected galaxies (at the same magnitude limit), the significance of the excess is low ($\approx 2\sigma$). This implies that the pairing fraction of the sub-mJy population is higher than that of local galaxies. This is because the frequency of interactions in optically selected samples has been shown to increase with redshift (Burkey et al. 1994). Therefore, the optically selected galaxy sample studied here, with a magnitude limit $R = 21.0$ mag, corresponding to a mean redshift $z \approx 0.25$ (Pozzetti, Bruzual & Zamorani 1996), already comprises a higher fraction of interacting systems than local galaxy samples.

Moreover, the similarity of the sub-mJy and 'field' galaxy close pair distributions in Figure 2 suggests that radio selection at a given optical magnitude limit does not guarantee a significantly higher fraction of interacting systems compared to optical selection (at the same limiting magnitude).

However, one should be cautious about this interpretation. Firstly, the statistical approach used here calculates the probability of a galaxy having a physically associated companion with projected separation $\delta\theta$ and magnitude R by estimating the expected number of galaxies brighter than R within radius $\delta\theta$. Therefore, for a given magnitude, R , the larger the separation, $\delta\theta$, the higher the probability, P , that the pair is a spurious alignment of the sky plane. For example, for $R \approx 20.0$ mag only pairs with $\delta\theta \lesssim 12$ arcsec are identified as potentially interacting for $P < 0.05$. Consequently, the estimator in equation (2) is sensitive to relatively close pairs ($\delta\theta \lesssim 12$ arcsec) and is likely to miss physically associated galaxies with larger projected separations. Additionally, due to resolution effects we can only identify candidate interacting systems with $\delta\theta \gtrsim 4$ arcsec. This angular separation corresponds to a linear size of 20 kpc ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) at $z = 0.25$, the median redshift of the sub-sample with $S_{1.4} \geq 0.4$ mJy, $17.0 \leq R \leq 21.0$ mag and available spectroscopic information (79 sources out of a total of 206). These very close pairs are also expected to

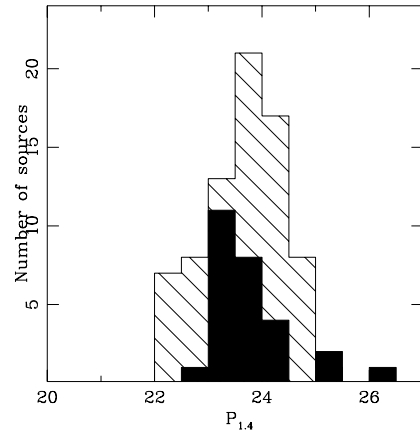


Figure 3. Radio power distributions for 'isolated' (hatched region) and paired (shaded histogram) radio sources (see text for details).

have high radio luminosity (normalised to optical luminosity; Read & Ponman 1998). Future high-resolution photometric observations have the potential to reveal the presence of very close pairs within the sub-mJy population, that remain unresolved in the present study.

Moreover, in our analysis we only consider the optically brightest ($R \leq 21.0$ mag) radio sources. These are likely to lie, on average, at relatively lower redshifts compared to optically fainter objects ($R > 21.0$ mag). The pairing fraction of the optically fainter sub-mJy sources remains to be explored.

A total of 27 out of 43 ($\approx 60\%$) faint radio sources for which our analysis indicates possible association with 'field' galaxies ($P \leq 0.05$), have available spectroscopic information. The sample consists of absorption-line systems (37%), Seyfert 1 or 2 type objects (15%), unclassified sources (30%) and star-forming galaxies (19%). For $P \leq 0.10$, the rel-

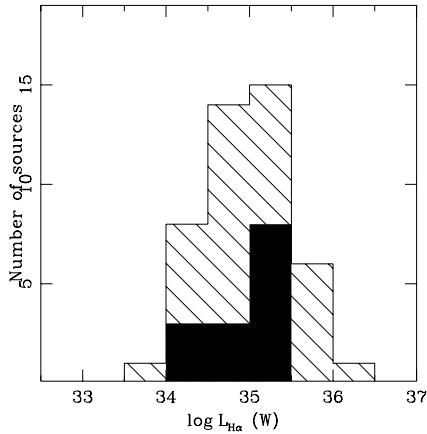


Figure 4. $\text{H}\alpha$ luminosity distribution for isolated (hatched region) and paired (shaded histogram) radio sources.

ative fraction of different types of sources is similar. The radio power distributions of these sources are compared in Figure 3 with those of the spectroscopic sample of optically identified radio galaxies with $S_{1.4} \geq 0.4 \text{ mJy}$ and $17.0 \leq R \leq 21.0 \text{ mag}$. The histogram for the $\text{H}\alpha$ luminosity distribution of the two samples is shown in Figure 4. There is no significant difference between the two populations in these Figures. Hummel (1981) also found no difference in the radio power distributions of isolated galaxies and galaxies in pairs. Moreover, interacting systems, although being on average more luminous at infrared or $\text{H}\alpha$ wavelengths compared to ‘field’ galaxies, exhibit significant scatter around their mean emission properties (Keel et al. 1985; Kennicutt et al. 1987; Bushouse et al. 1988). This is attributed to (i) the relative velocities of the interacting galaxies (ii) the properties of the galactic disks, especially in relative weak encounters and (iii) the time scale of the induced star-formation relative to that of the gravitational encounter (Kennicutt et al. 1987). Hence, a relatively small sample like the one considered here, cannot reveal any correlations between pairing fraction and optical emission-line luminosity. Moreover, close pairs with projected separations $\delta\theta < 4 \text{ arcsec}$ remain unidentified in the present study. These pairs are also likely to be on average more luminous at optical and infrared wavelengths compared to systems with larger separations (Read & Ponman 1998).

Additionally, our analysis shows that galaxies with non-thermal nuclear activity are more frequently found in associations ($\approx 50\%$) compared to radio sources heated by hot stars. This is because there is only a small number of star-forming galaxies ($\approx 20\%$ of the spectroscopic sample; Georgakakis et al. 1999) in the sub-sample with $S_{1.4} \geq 0.4 \text{ mJy}$. This is dominated by absorption-line systems, Seyfert 1 and 2s, constituting $\approx 64\%$ of the $S_{1.4} \geq 0.4 \text{ mJy}$ spectroscopic sample (Georgakakis et al. 1999).

7 CONCLUSIONS

In this study an objective and quantifiable statistical approach is employed to assess the significance of tidal interactions in the evolution of the faint radio sources, detected in a deep and homogeneous radio survey with available photometric and spectroscopic data. In particular, the pairing fraction of the faint radio population is compared with that of optically selected ‘field’ galaxies. We found evidence for an excess of close pairs around optically identified faint radio sources, albeit at a low significance level. This implies that (i) the frequency of interacting systems within the sub-mJy population is higher than that in local galaxy samples and (ii) the pairing properties of the sub-mJy radio sample (with the given biases such as resolution effects) are not significantly different from those of ‘field’ galaxies at the same magnitude limit.

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